

EO-1 Advanced Land Imager Calibration and Performance Overview

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ABSTRACT

The pre-launch measurements and tests required for calibration and characterization of the Advanced Land Imager (ALI), which will be flown on NASA's EO-1 mission, have been completed. The instrument level performance testing was conducted at MIT Lincoln Laboratory with the ALI in an operational environment. The overall calibration strategy, which includes both pre-launch and post-launch components, will be described in this paper. The fundamental sensor calibration data comprise five measurement categories: angular position in object space for each pixel; normalized spectral response functions; response coefficients; zero signal offsets; and modulation transfer functions. Performance and characterization tests include measurements of noise, SNR, linearity, repeatability, image artifacts, stray light rejection, and cross-talk. An overview of the facilities, equipment, tests and results is presented here.

Keywords: calibration, EO-1, imaging, ALI, multispectral

1. INTRODUCTION

The first Earth-Observing satellite (EO-1) in the New Millennium Program (NMP) of the National Aeronautics and Space Administration (NASA) will carry an Advanced Land Imager (ALI) with multispectral imaging capability. The NMP missions are structured to accelerate the flight validation of advanced and enabling technologies. These technology validations are accomplished in the context of science measurement objectives. The focus of EO-1 is the validation of those technologies relevant to future Landsat missions. The ALI has been designed to produce images directly comparable to those from the Enhanced Thematic Mapper Plus (ETM+) of Landsat 7. The ALI will also establish data continuity with previous Landsats and demonstrate advanced capability and innovative approaches to future land imaging. The EO-1 satellite will fly "in formation" with the Landsat 7 satellite in a sun-synchronous, 705 km orbit with a 10:01 AM descending node. That is, it will be in an orbit that covers the same ground track approximately one minute later than the Landsat 7 satellite. Images of the same ground areas obtained by the two instruments at nearly the same time will be available for direct comparison by members of the science community. Accordingly, the basic field of view, angular resolution, and spectral bands are matched to those of the ETM+. Furthermore, the evaluation of on-orbit performance of the ALI technologies will provide timely information for the development of the next generation Landsat. The EO-1 satellite is co-manifested with Argentina's SAC-C (Scientific Applications Satellite) and is scheduled for launch from the Western Test Range on a Delta 7320 on 15 December 1999. More detailed descriptions of the EO-1 mission and the ALI are given elsewhere¹⁻³.

Overall direction of the EO-1 mission and acquisition of the spacecraft is being carried out by the Goddard Space Flight Center (GSFC) of NASA. MIT Lincoln Laboratory developed the Advanced Land Imager with NMP Instrument Technology and Architecture team members Raytheon Systems Santa Barbara Remote Sensing (SBRS) for the focal plane system and SSG Inc. for the optical system. Lincoln Laboratory was responsible for the design, fabrication, test and development of the instrument, the software and databases for calibration, and will be responsible for the initial on-orbit performance assessment. Detailed descriptions of ALI testing, data processing, and performance results are given elsewhere⁴⁻¹³. Here we present an overview of the ALI calibration and characterization plan, the facilities and equipment employed, and some preliminary performance results.

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2. ALI CALIBRATION PLAN

The calibration and characterization plan for the ALI has both pre-launch and in-flight components. The objectives are to characterize the overall instrument performance and to determine all instrument parameters required to generate accurate estimates of spatial, spectral and radiometric image quantities. The ALI performance requirements were guided by the Landsat 7 specification¹⁴ and were generated in concert with Landsat, EOS and EO-1 calibration scientists. The requirements were also constrained by the primary NMP mission objective, which is the validation of key technologies in flight. The instrument performance & verification tests included: measurements of noise, repeatability, polarization dependencies, temperature transient response, saturation recovery, image artifacts, and stray light rejection. The overall strategy is illustrated in Figure 1.

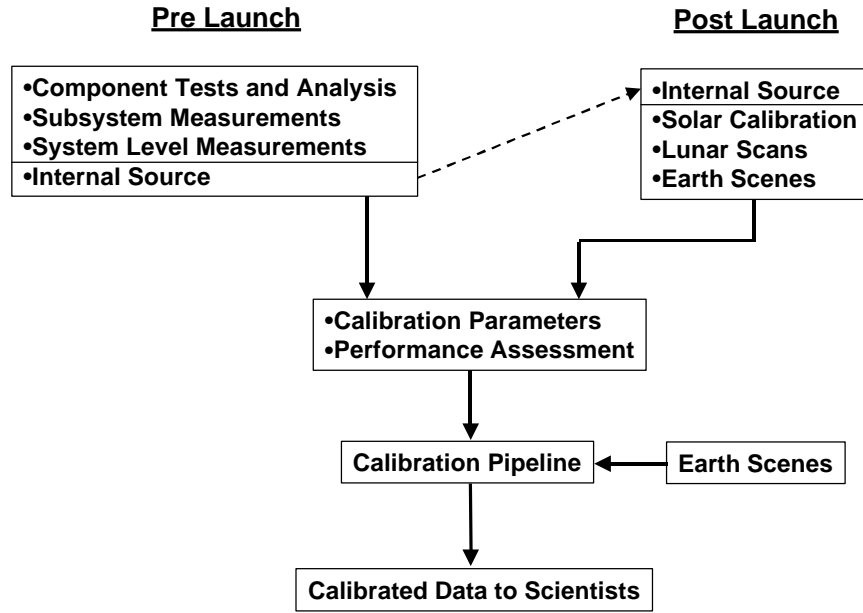


Figure 1. The EO-1 ALI pre-launch and post-launch calibration strategy

The sensor calibration data comprise five measurement categories and are established for each detector channel (N). These are:

2.1 Normalized spectral response function: $F_N(\lambda)$

This function represents the relative response of a detector channel to a constant monochromatic radiance ($W/cm^2 \cdot sr \cdot \mu m$) at the entrance aperture of the sensor as a function of wavelength. The function is normalized to unity at the peak. These functions define the in-band radiance (L_λ) at the entrance of the sensor:

$$L_\lambda = \int L(\lambda) F_N(\lambda) d\lambda, \text{ where } L(\lambda) \text{ is the spectral radiance at the entrance of the sensor.}$$

2.2 Pixel angular position in object space: $(x, y)_N$

Each detector will respond to the radiance from different angular directions. This direction is determined both by the location of the detector in the focal plane of the telescope and the distortion from the optical system. Undistorted reconstruction of the scene requires accurate knowledge of the relative angular position of each detector in object space. These are measured relative to an arbitrary bore-sight direction.

2.3 Modulation transfer function: MTF_N

The MTF for each detector channel is a two dimensional function of the spatial frequency of the imaged scene. It represents the magnitude of the Fourier transform of the detector channel's system response as a function of angle. The MTF is a measure of image sharpness and is used in quantitative image reconstruction.

2.4 Zero signal digital number offset: dn_0 ,

This is the digital number offset that each detector channel has when there is no input radiance. These offsets remain fairly constant, however they are measured for every data collection event to improve accuracy.

2.5 Response coefficient: C_N ,

These convert raw digital numbers (dn) to estimates of in-band radiance (L^*_λ), i.e., $L^*_\lambda = C_N (dn - dn_0)$. Although C_N is approximately constant over the full dynamic range it is in general a weak function of $(dn - dn_0)$. This is accounted for in the calibration process. Each detector channel has 16 functional representations for C_N , one for each integration time.

These five calibration “parameters” are built up from all the pre and post launch measurements. A summary of this process, including the relative weight of each measurement, is shown in Table 1. Note that there is at least one primary measurement for each of the five “parameters” and that for the spectral response functions there is no on-orbit measurement of significant value.

	Spectral Response Function	Response Coefficient	Zero Signal Offset	Pixel Angular Position	Modulation Transfer Function
Component Tests and Analysis	●	○	—	—	○
Subsystem Tests: Telescope and MS/Pan	—	○	○	○	○
Instrument-Level Laboratory Tests	●	●	○	●	●
On-Orbit Measurements:					
Solar Diffuser	—	●	—	—	—
Closed Aperture	—	—	●	—	—
Internal Source	—	○	—	—	—
Lunar Scans	—	○	○	—	○
Earth Scenes	—	○	—	○	○

Table 1. ALI calibration matrix. Primary measurements are denoted by solid circles and secondary measurements by open circles. A dash indicates that no data of any significant value is obtained.

2.6 Pre-launch calibration and characterization strategy

The pre-launch component, which is essentially completed, began with testing and analysis at the component level. This process continued through subsystem and system level testing. The objective was to generate initial estimates of the sensor's spatial, spectral, and radiometric characteristics and then track the performance throughout the development phases of the instrument. This provided an early indication of any test setup errors, analysis errors, or performance anomalies. Moreover, since this process employed a number of independent and complementary calibration methods, consistency in projected performance increased the confidence of the final calibration parameters. Pre-launch testing and calibration were conducted

under mission-like conditions including appropriate environmental conditions, and the full range of signal levels, wavelengths and spatial frequencies. The internal calibration source was used throughout ground testing as a health check and to measure stability of performance. This was especially useful during environmental testing as a means of verifying satisfactory performance. Some measure of absolute radiometry is established for the internal calibration source by transfer to the integrating sphere calibration. The design of the internal source is described by Mendenhall et al.⁸

2.7 In-flight calibration strategy

The post-launch calibration component will begin with internal source measurements. This is the only direct link to the pre-launch calibration and establishes continuity of performance from ground to space. The on-orbit absolute calibration relies primarily on the solar calibration, which is described by Mendenhall et al.⁸ Lunar scans are planned and will be used as a measure of image quality and some (TBD) measure of radiometric accuracy. Finally, well-characterized ground scenes will be used for both image quality assessment and radiometry. The on-orbit calibration plan is intended to contain adequate capabilities for cross checks and diagnostic tests.

3. FACILITIES AND EQUIPMENT

All testing and calibration of the ALI was carried out in a Class 1,000 clean room at Lincoln Laboratory. The overall layout of the clean room facility is illustrated in Figure 2. Most of the major assembly, such as integration of the focal plane with the optical system and some functional measurements requiring only the VNIR detectors, were done under the class 100 laminar flow module. The definitive calibration and characterization measurements on the ALI were performed while the instrument was in the thermal vacuum chamber that contained a liquid nitrogen-cooled shroud. The SWIR detectors of the ALI required cooling to 220K and could not be tested otherwise. Moreover the entire ALI was operated at flight temperature and vacuum conditions. Three major optical test configurations were used for most of the key measurements. These consisted of a Schmidt sphere imaging collimator, an off-axis parabolic collimator, and a 30 inch integrating sphere with a spectro-radiometer.⁴⁻¹¹ With the ALI in the vacuum chamber, optical measurements were made through a 12 inch diameter fused-silica window. This window was well characterized for both wavefront error and spectral transmission. A summary of the ALI performance tests and the corresponding test configurations is given in Table 2. The Landsat transfer calibration was the only test not done in the clean room.

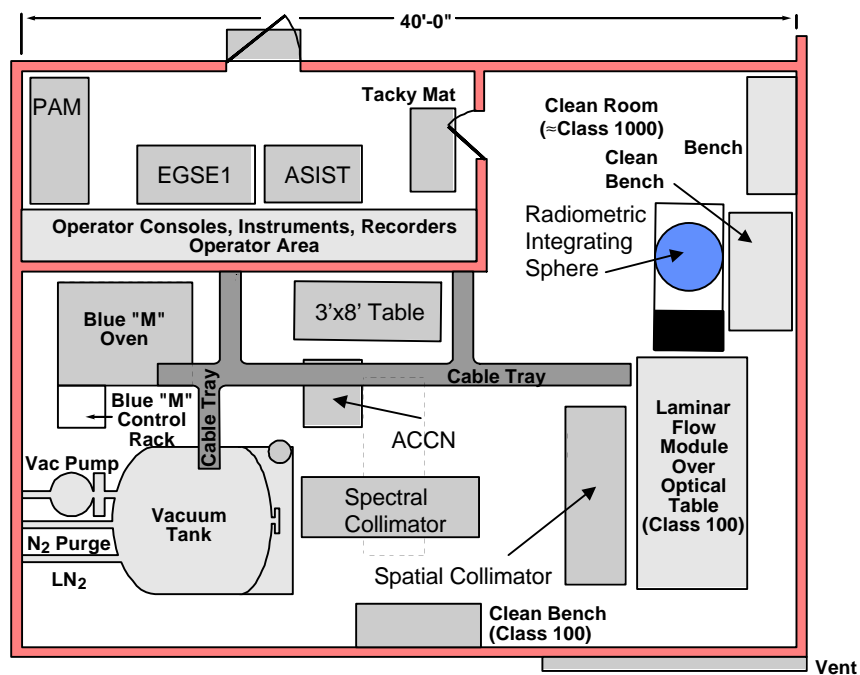


Figure 2. ALI class 1,000 clean room facility used for assembly, performance testing, and calibration

TASK	OPTICAL TEST CONFIGURATION
FPA alignment	Schmidt sphere imaging collimator with knife edge
Focus verifications	Schmidt sphere imaging collimator with knife edge
End-to-end imaging	Schmidt sphere imaging collimator with scene
MTF measurements	Schmidt sphere imaging collimator with knife edge
Pixel line-of-sight	Schmidt sphere imaging collimator with Ronchi ruling
Image of filters	Schmidt sphere imaging collimator with a CCD camera
Reference cube alignment	Autocollimating theodolite
Spectral calibration	Off-axis parabolic collimator and grating monochromator
Polarization tests	Off-axis parabolic collimator with Glan-Thompson prisms
Solar calibration functional test	Off-axis parabolic collimator with a 1kW Xe arc lamp and a Spectralon diffuser
Radiometric calibration	Integrating sphere and spectroradiometer
Landsat transfer calibration	Integrating sphere and GSFC LXR
Internal source transfer calibration	Internal source

Table 2. Summary of the ALI performance tests and the corresponding test configurations.

4. PRELIMINARY RESULTS

The ALI performance and calibration data that were collected are still in the process of being analyzed. Detailed results to date are reported by Hearn et al,⁴ Mendenhall et al,^{5,6} Evans et al,¹² and Viggh et al.^{11,13} This section provides some representative data which illustrate the performance of the ALI.

The internal calibration source provides three illumination levels plus a zero signal reference. It is mounted on the side of the telescope metering truss and illuminates the FPA from an angle of about 30° relative to the normal. This produces a gradient in the illumination and a shadowing near the edges of the four SCA's caused by the filter bezels. An example of the detector outputs for the three lamp levels is shown in Figure 3. The zero signal offsets have been subtracted from these data. This particular example shows the signals for all 1280 detectors in Band # 4. A very useful and sensitive diagnostic technique for determining the stability of the ALI consisted of monitoring the outputs of the detectors during a series of tests or over a period of time. The ratio of outputs for each detector from Band # 4 measured 5 days apart is shown in Figure 4.

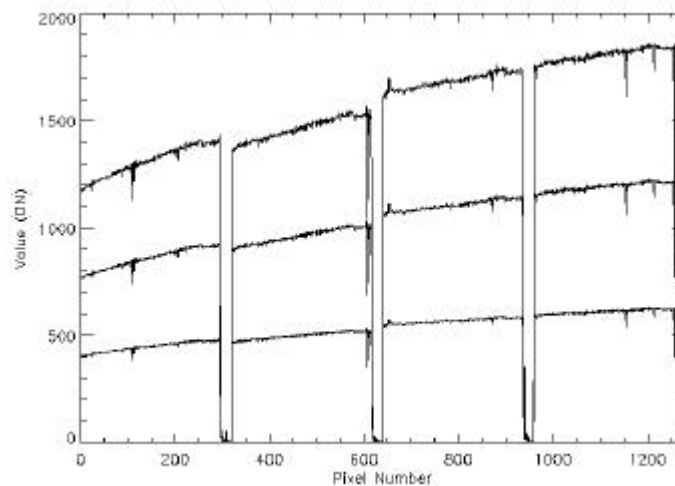


Figure 3. Band # 4 detector outputs for the three internal calibration lamp levels.

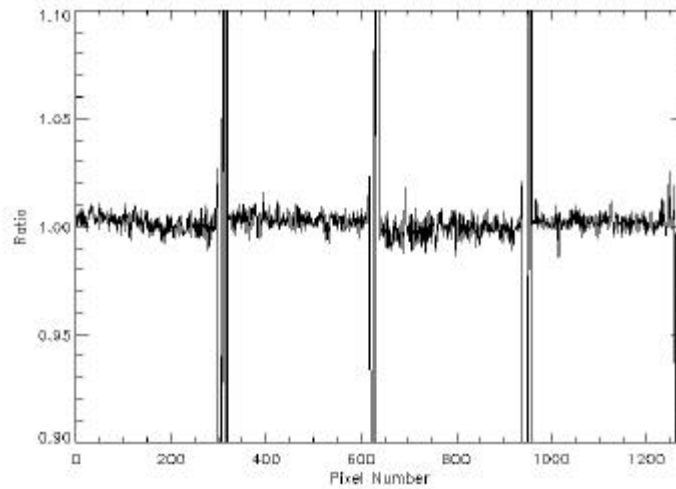


Figure 4. The ratio of outputs for each detector from Band # 4 measured 5 days apart.

The overall imaging performance was verified by end-to-end imaging tests in which collimated target images, scanned at the earth rate that will be seen on-orbit, were injected into the ALI. The reconstructed and calibrated image of a Star Burst target for the Pan Band is shown in Figure 5. For this case the image was generated with all four SCA's. At the inner circle of the Star Burst the lines are about 1.8 pixels wide (equivalent to 18 m on the ground) and can easily be resolved in the expanded view.

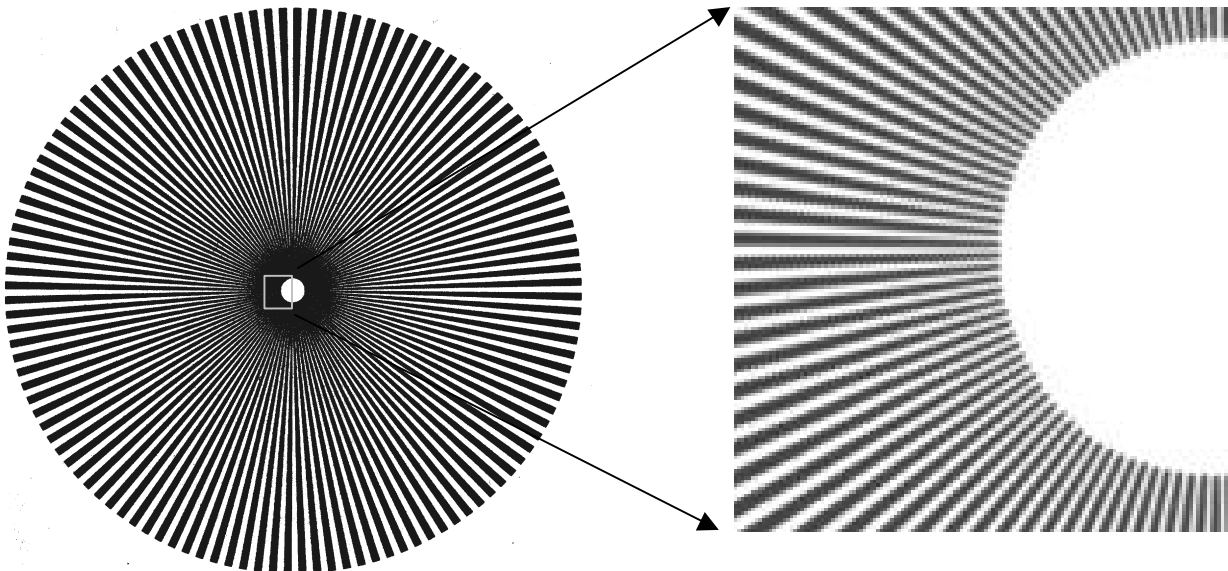


Figure 5. End-to- end reconstruction of a Star Burst image in the PAN Band.

The ALI is designed to operate without saturating over the full range from 0% to 100% albedo with 12 bit resolution. The instrument was calibrated over this full range. An example of the output of one detector over its full dynamic range is given in Figure 6. For this example the input was varied by changing both the radiance and the ALI integration times. The full dynamic range defined as the ratio of the saturation flux to the RMS noise is in this case 3.8×10^3 .

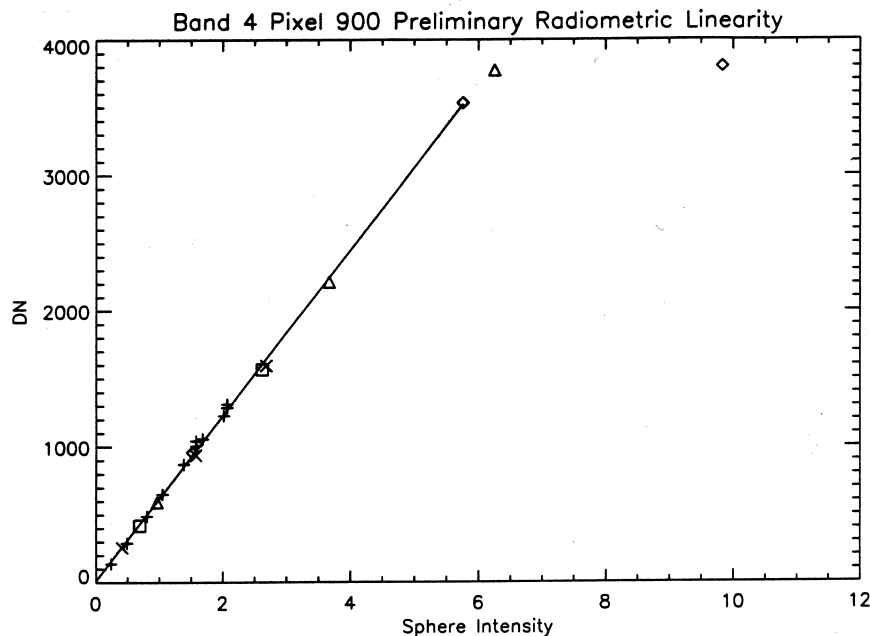


Figure 6. ALI dynamic range and linearity for a typical pixel (# 900, Band # 4)

One of the most significant performance aspects of the ALI is the high SNR that is achieved with such a small optical aperture (12.5 cm). This is illustrated in Figure 7, which summarizes the average SNR of all the bands for a 5% earth surface reflectance. These results are compared to the SNR of the ETM+. In the bands that are common to both instruments, the expected ALI SNR ranges from 4 to 10 times greater than ETM+. This enhanced SNR is the result of the large number of detectors and the increase in integration time inherent in the push broom architecture.

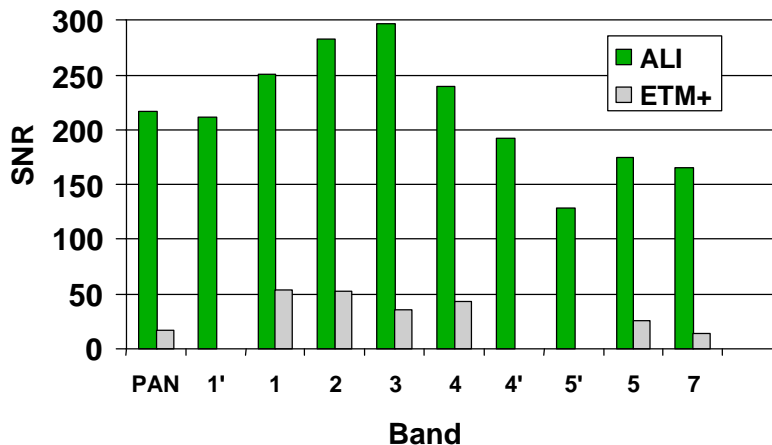


Figure 7. ALI and ETM+ SNR performance for a 5% earth surface reflectance

5. SUMMARY

The EO-1 Advanced Land Imager has undergone extensive pre-launch characterization and calibration. Although data analysis and performance assessments are still in progress, preliminary results indicate superior performance in resolution, image quality, SNR, dynamic range, radiometric accuracy, and repeatability. This performance has been achieved in a sensor of considerably smaller size, lower weight, and requiring less power than previous instruments with similar Earth observing objectives. The EO-1 mission should successfully flight-validate the New Millennium Program technology objectives.

ACKNOWLEDGEMENTS

This work was sponsored by NASA/Goddard Space Flight Center under U.S. Air Force Contract number F19628-95-C-0002. Opinions, interpretations, conclusions, and recommendations are those of the authors and are not necessarily endorsed by the United States Air Force. The authors acknowledge the support and contributions from Dr. Stephen Ungar of NASA/GSFC.

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